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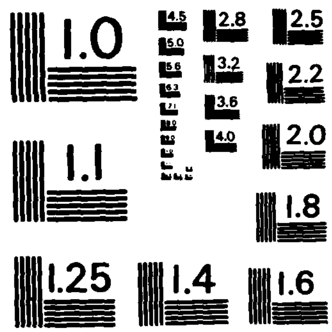


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The Laboratory for Image and Signal Analysis conducts a broad program of research in computer vision, image processing and architectures for image processing. During the period of this report, several projects were completed including those on positioning and tracking of objects moving in space, parallel image processing, 3-D representation and recognition from range data and a normalized quadtree representation. A new approach to the problem of tracking of objects in space is formulated which is significantly simpler and robust in solution. Previously available quadtree description of objects is modified


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to develop a new description called normalized quadtree representation. This representation is found to be compact as well as useful in recognition of objects. A methodology for analysis of architectures for parallel image processing is proposed. Our research advocates an application-drive approach for using parallel architectures for image processing.

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Final Scientific Report

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Principal Investigator: Professor J. K. Aggarwal

## Final Scientific Report

## AFOSR Contract No. F49620-83-K-0013

## Abstract


The Laboratory for Image and Signal Analysis conducts a broad program of research in computer vision, image processing and architectures for image processing. During the period of this report, several projects were completed including those on positioning and tracking of objects moving in space, parallel image processing, 3-D representation and recognition from range data and a normalized quadtree representation. A new approach to the problem of tracking of objects in space is formulated which is significantly simpler and robust in solution. Previously available quadtree description of objects is modified to develop a new description called normalized quadtree representation. This representation is found to be compact as well as useful in recognition of objects. A methodology for analysis of architectures for parallel image processing is proposed. Our research advocates an application-driven approach for using parallel architectures for image processing.

## Scientific Report

During the period December 1, 1982 through January 31, 1985, our group made 21 presentations, published 18 papers in refereed journals, 15 in conference proceedings, and 5 technical reports. Final versions of 5 additional papers were prepared and will appear in journals in the next reporting period. A complete listing of these activities is provided at the end of this report. The group devoted its efforts to six areas of research briefly described in the following. The areas are:

1. 3-D Representation and Recognition from Range Data
2. Positioning and Tracking Objects in Space
3. Algorithm Driven Architectures for Image Processing
4. A Normalized Quadtree Representation and a Volume/Surface Octree Representation
5. Analysis of a Model for Parallel Image Processing
6. Determining Motion Parameters Using Intensity and Range Information

## 1. 3-D REPRESENTATION AND RECOGNITION FROM RANGE DATA

Range (depth) data provide an important source of 3-D information. Range data implicitly contain information about the shape of the surface of objects because the coordinates of points on the surface of these objects can be easily recovered from them. Recognizing objects given range information is an important problem in computer vision tasks and has a wide variety of applications such as assembly of industrial parts, automatic selection and inspection, etc.

Range data may be derived from intensity images or through direct measurement sensors. Analyzing intensity images of three-dimensional scenes to obtain depth information has received considerable attention in recent years. The basic approach to determine three-dimensional structure from intensity images is to use cues such as shading, texture, shadow edges, and other image features, to derive constraints on the structure of objects that may be present in a scene. Even though each constraint may allow many different structures, frequently the unique structure can be determined by combining a number of constraints. One obstacle to general vision systems utilizing such an approach is the number of computations required to apply the constraints.

The use of direct range measurements can simplify the problems associated with deriving three-dimensional structure from intensity images. This is due to the fact that three-dimensional coordinates of visible points in the scene are provided directly by the ranging device. Our goal here is to develop algorithms for recognition of objects from range data. The recognition of objects may be achieved according to the following paradigm:

- building object representation,
- feature extraction,
- and matching object descriptions to models of objects.

Most of the existing approaches make explicit assumptions about the underlying surfaces in the scene. For example, some of the early approaches assume that the scene is composed of objects with planar faces. Although techniques do exist for describing scenes composed of both planar and curved objects, they make explicit distinction between these two types in the reconstruction process. Hence, there is a need for algorithms that can treat planar and curved objects in a homogeneous fashion. We have developed such an algorithm which builds object descriptions in terms of regions that are a collection of surface primitives homogeneous in certain intrinsic surface properties. The algorithm is not restricted to polyhedral objects nor is it committed to a particular type of approximating surface. The algorithm has been tested on synthetic and real data.

The second phase of this research involves feature extraction. A crucial step in the recognition of objects is the selection of object features or shape descriptors that capture invariant geometrical properties of objects. Shape features may be quantitative or qualitative. Qualitative features are symbolic descriptors (e.g., spherical, elliptic, etc.) Numerical values are associated with quantitative features for example, surface area, average curvature, etc. A number of such descriptors are currently under investigation for use in deriving rich object descriptions.

The third phase of this research involves matching these rich object descriptions to model descriptions stored in a database. Matching may be viewed as a labelling process that is the function of the matching algorithm is to identify each object in a scene and assign a label/identity to that object. Several matching strategies have been proposed in literature, most of them using features that are not invariant to viewpoint and are very domain specific. A cascaded matching strategy is currently under investigation. The first stage of the cascade involves an efficient way of eliminating possible candidate models for matching. This is done by using a bin counting technique. The second stage of the cascade involves assigning most probable model candidate to the object, using a relaxation technique. The matching algorithms will be restricted to the use of constraints drawn from the domain of objects.

As a general technique for computing visible surface structure from range data, extracting viewer independent surface properties that are useful in recognizing objects and matching (to achieve the goal of recognition) using domain constraints, this research will be relevant in advancing the state-of-the-art in many applications.

The first phase of this research has been completed. This phase is concerned with the representation of visible 3-D object surfaces by regions that are homogeneous in certain intrinsic surface properties. The approach consists, first, of fitting smooth patches to the object surfaces. Principal curvatures are then computed and surface points are classified accordingly. Such a representation scheme has applications in various image processing tasks such as graphics display and recognition of objects.

An algorithm has been developed for computing object descriptions. The algorithm divides the input data array into windows and fits approximating surfaces to windows of data that do not contain any discontinuities in range. The algorithm is not restricted to polyhedral objects nor is it commited to a particular type of approximating surface. It uses tension splines which make the fitting patches locally adaptable to the shape of the surface of objects. Maximal regions are formed by coalescing patches with similar intrinsic, curvature-based properties.

Regions on the surface of the object can be subsequently organized into a labelled graph representation, where each node represents a region and is assigned a label depicting the type of region and a containing set of feature values computed for that region. Issues concerning the organization of these regions and matching the object descriptions with models will be the focus of further research. A report documenting preliminary results is under preparation.

## 2. POSITIONING AND TRACKING OBJECTS IN SPACE

In this research we take a fresh look at an old problem, however an important problem of current interest: that of estimating the position and motion of an object in space from the observation of a small number of points in two distinct images of the object. This problem has been and still is the center of considerable attention because of the many potential applications.

In general, past approaches to the problem have developed equations using directly projective relations for the observed points and which involved both the three-dimensional coordinates of the points and the parameters of motion. Then a typical counting argument dictated the number of points that had to be observed in order to solve the relations. This generally led to a large set of complicated non-linear transcendental equations. To reduce complexity, either simplifying assumptions were introduced (e.g. parallel projection to model imaging, restricted motion such as pure translation or pure or small-angle rotation, known object geometry, etc.) or one relied on additional constraints such as the gradient intensity constraint. Linear methods were also considered when a larger number of points could be observed in the images.

Our approach differs from others being characterized by the combination of the following properties:

(1) It treats the general case of structure and motion, (2) Instead of using directly projective relations for the observed points, it exploits the principle of conservation of distances with respect to rigid object motion, (3) It separates the problem of estimating object position completely from that of determining motion parameters. This split renders the first problem much

simpler and the second an almost trivial one, (4) Its resolution is rather stable numerically, (5) The solution is unique up to a global scale factor, a reflection in space, and a singular configuration.

The main idea in our method is the use of the principle of conservation of distances in rigid objects. This principle, which is the subject of a theorem in kinematics of solids, simply states an obvious fact: distances in a rigid configuration of points do not change during motion. This characterization of rigid motion can lead to powerful formulations of various structure and motion problems.

In this study, we consider a set of points in a static, rigid environment. First, we would like to point out that the input to our method consists of positions of image points and not optical flow. Now, if we call $S_1$ and $S_2$ the camera coordinate systems at two distinct viewpoints (obtained, say by a moving camera at two distinct instants of time or by two cameras from two different viewpoints) then we write that distances between points of the rigid environment are the same whether expressed in $S_1$ or in $S_2$. However, there is no mention, at this stage, of the transformation that takes $S_1$ into $S_2$ or vice versa. Also, we use the scalar notation for projective relations. With this notation, each observed point contributes 2 variables (one for each coordinate system) and each pair of points gives one equation. If we take 5 points and set one variable arbitrarily to fix the global scale of the object, then we end up with 10 equations in 9 unknowns. Although this method does not provide an economy of points compared to some other methods, we nevertheless arrive at a compact and robust formulation of the problem; the second order equations we obtain are simple and involve only some of the variables and can be solved quite

efficiently using existing iterative numerical methods. Moreover, the solution is unique up to a singular configuration and a reflection, once we fix the global scale factor.

After we determine the position of points, solving for the motion matrix is a simple matter of solving a 4 x 4 linear system of equation using 4 of the points. The actual parameters of motion can then be recovered analytically from the motion matrix.

The algorithm for computing the position of points has been tested on camera-acquired pictures of real objects as well as on synthetic data. Results indicate that this approach to structure and motion computation is indeed accurate and robust.

## 3. ALGORITHM DRIVEN ARCHITECTURES FOR IMAGE PROCESSING

Image processing architectures are burdened with enormous data throughput and processing requirements. Current commercially available video camera systems provide gray level intensity information at the rate of approximately $2^{28}$ bits/sec. Multispectral and high resolution imagery provide about two orders of magnitude more data/sec, and projections of future space and military applications indicate several orders of magnitude increase in data throughput and processing requirements. Even without the constraints of real time or high speed processing, the computational needs are formidable and efficient solutions are beyond the capabilities of conventional uniprocessor systems. Future systems must make use of extensive parallel processing to adequately satisfy these requirements.

In developing parallel processing solutions to problems in image analysis and understanding, one is confronted by two problems. The first is formulating parallel algorithms and the second is the efficient utilization of parallel architectures for the implementation of these algorithms. A number of research efforts have focused on the problems of matching the requirements of image processing algorithms and the capabilities afforded by parallel architectures. Several efforts have advocated the dedicated hardware implementation of algorithms. This approach is based on the decreasing cost of hardware but neglecting rapidly rising design costs. Other efforts are what we will refer to as architecture driven. A specific parallel architecture, e.g., mesh connected array, ring connected array, etc., is chosen. Then the development of parallel algorithms based on this architecture is pursued. Such an approach precludes determining the most appropriate architectural solutions. In addition, it is

usually algorithm specific necessitating redevelopment of algorithms once the system organization is changed. Finally, more general mathematical formulations have been pursued, such as mapping graphs representing computations, onto graphs representing architectures e.g., the mapping problem. In such approaches, due to the generality of the formulations, efficient solutions are indeed rare. More importantly, they presume the existence of parallel solutions, which is often not the case.

Our research advocates and presents an application-driven approach for identifying and utilizing parallel architectures for image processing. A parallel processing model is proposed. This model possesses several unique features and forms the basis for methods to formulate parallel versions of sequential image processing tasks. It is shown how one can analyze the communication and computation requirements resulting from these formulations in order to determine constraints on architectural features which must be satisfied in order to achieve predefined performance goals. These constraints may serve as benchmarks in selecting an architecture for a specific application, or as initial estimates in designing a new system.

## 4. A NORMALIZED QUADTREE REPRESENTATION AND A VOLUME/SURFACE OCTREE REPRESENTATION

Quadtrees are hierarchical data structures used for compact representations of two dimensional images. A quadtree is generated by dividing an image into quadrants and repeatedly subdividing the quadrants into sub-quadrants until each quadrant has uniform color (e.g., '1' or '0' in a binary image). The root of a quadtree corresponds to the image it represents. A node in a quadtree either is a leaf (terminal node) or has four son-nodes (non-terminal) node). Each son-node is associated with a quadrant of the block corresponding to its father-node.

Several excellent reviews of the subject are available in the literature. The advantage of the quadtree representation for images is that simple and well-developed tree traversal algorithms allow fast execution of certain operations such as superposition of two images, area and perimeter calculations, moments computation, etc. Other researchers have shown that the quadtree representation of images yields substantial data compression over ' variety of source images. In their experiments, image compression ratios ranging between three to one and thirty-three to one were found, with five or six to one being the general compression factor.

However, the quadtree representation has certain disadvantages. The quadtree representation of an object in an image is heavily affected by its location, orientation and relative size. A small change in these parameters will generate different quadtrees. One may eliminate the effect due to the translation of objects in an image by defining a normal form for quadtrees.

Assuming that the size of an image lies between $2^{N-1}$ and $2^N$, the image is moved around a region of size $2^{N+1}$ to find a minimal cost quadtree in terms of the number of nodes. This quadtree representation is unique for any image over the class of translations. However, the problem arising from rotations and size change still remains.

In this investigation, we propose a representation scheme, the normalized quadtree representation, which is invariant to object translation, rotation and size change. Instead of generating a quadtree for the entire image, a normalized quadtree is generated for each object in the image. The object is normalized to an object-centered coordinate system, with its centroid as the origin and principal axes as coordinate axes, and then scaled to a standard size (a $2^N$ x $2^N$ image). In this way, the normalized quadtree of an object is dependent only on the shape of the object, but not affected by its location, orientation or relative size. In other words, the normalized quadtree representation can be utilized as a shape descriptor. In addition, information related to the size, the position and the angle of the major principal axis of the object in the image may be retained enabling reconstruction of the object as it appeared in the image. According to Pavlidis' classification, the normalized quadtree representation is an information preserving shape descriptor.

A report has been prepared which briefly reviews the notions of moments and principal axes. The algorithm for the generation of quadtrees is then described followed by the description of the normalized quadtree representation and some examples. Finally, we describe the application of the normalized quadtree representation to two problems: shape matching and computation of principal moments. The report considers several examples of the generation and

application of the normalized quadtree representations of a set of eight airplanes. The normalized octree representation and possible applications of the normalized quadtree representation for the modelling of three dimensional objects are also discussed.

The octree structure for the representation of 3-D objects is an extension of the quadtree representation of 2-D images. In general, it is generated from the 3-D binary array of the object it represents. However, the acquisition of 3-D array itself is a non-trivial problem. In the continuation of the above study, we generate the octree of an object from its three orthogonal views exploiting the volume intersection technique. To incorporate the surface information into the octree representation, which is basically a volume description, we propose a multi-level boundary search algorithm to find all the interfaces between black and white blocks. The information of each such interface is then stored in one of the two corresponding nodes. This makes the octree representation compact, informative, and especially useful for continuous displays and object recognition tasks. All the algorithms developed in this study are essentially tree traversal procedures and therefore are suitable for implementation on parallel processors. In addition to developing the octree representation, we are investigating its applicability to recognition tasks.

## 5. ANALYSIS OF A MODEL FOR PARALLEL IMAGE PROCESSING

In the recent past there has been a great deal of attention focused on the design and implementation of parallel architectures to meet the computation demands of image processing and system design has followed two distinct paths. Low level operations which typically form the bulk of the computation and possess comparatively, a few well characterized operations, have been investigated for dedicated implementation. Based on descriptions of the algorithm, advanced VLSI design automation techniques are in the process of being developed to realize optimal dedicated low level architectures. On the other hand, high level processing characterized by widely varying data structures and computations, requires more flexible architectures for efficient operation. Multiple processors connected by dynamically reconfigurable networks have been investigated for the implementation of several algorithms established the utility of parallel image processing and provided some insight into the general problems encountered in constructing parallel tasks.

However, at this point it is still not evident what architectures are "best" suited for image processing in general, or for a given application in particular. It is equally uncertain how one may go about determining those which are. Though dedicated implementation provides high speed performance, their range of application is extremely narrow. On the other hand, the flexibility required of high level processes is achieved with some sacrifice in processing speed and increased system complexity. For general purpose image processing, what is required is the capability for uniform teatment of applications by way of a methodology, so that alternate choices can be compared and contrasted in determining the best solutions. Techniques should take into

account the underlying parallel tasks. Therefore, the overall problem of determining suitable parallel architectures for general purpose image processing encompasses the following:

1) being able to determine the requirements of parallel image processing tasks,

2) characterization of the capabilities of an architecture that is to host the computation and

3) techniques for "matching" the results of 1) and 2).

The present investigation addresses the problem 1) above and discusses how it affects choices in 3). Some solutions to problem 2) above are discussed elsewhere. The basic assumptions made about the architecture that will perform the processing are embodied in a parallel architecture model that is considered here. With this specification of the target machine, a synchronous parallel processing model is proposed for image analysis. Given a description of the algorithm and data structures to be operated upon, techniques are presented for constructing parallel tasks and specifying the communication requirements between them. Such a construction would produce an instance of the proposed processing model. An analysis of the parallel tasks constructed in this manner to illustrate how the model may be useful in determining a high level specification of the "best" architecture for a given application is considered. In addition, given pre-defined performance levels such as real time processing, it is shown how one may arrive at initial estimates of the capabilities of the components of the architecture, that are required to achieve these performance goals, e.g., number and speed of the processing elements, relative speed of

operation of communication and processing, etc. These estimates would provide a starting point for a designer prior to the refinement down to a complete detailed design. Examples are considered to illustrate the utility of the model and the techniques used to analyze an instance of the design. A report has been prepared and been submitted for publication.

## 6. DETERMINING MOTION PARAMETERS USING INTENSITY AND RANGE INFORMATION

The use of image processing techniques to derive motion parameters has been the subject of several recent research efforts. The use of intensity domain information has typically encountered difficulty imposed by the fact that from a single two-dimensional projection of three-dimensional scene, one may not determine the 3-D coordinates of any point in a scene. This arises since the projected point may result from any point lying on a line connecting it and the lens center. To determine the position of a point from intensity, at least two views are necessary. For motion parameter calculation correspondence among feature points in various views must be established and a complex systems of equations (which are frequently nonlinear) must be solved. We briefly review several of these methods to illustrate the complexity in the multi-view intensity domain.

Ullman developed trigonometric equations that derive object structure from two views of four points if it is known a priori that the transformation is a translation and a rotation about a single axis. Our early work has developed a method by which motion parameters may be derived from two views of five points but we are forced to solve a system of nonlinear equations. Nagel notes similar results.

For purposes of robot guidance and obstacle avoidance, Moravec presents an integrated system of vision hardware and software. His mobile vehicle has a camera mounted on a horizontal track so that when the robot is stationary it can slide the camera to any one of nine positions along the track. By determining correspondence in the separately derived images and knowing the relative

positioning of each of the camera locations, his system is able to determine the distance of objects while the robot is stopped. By examining several views (as seen by the robot at different positions) it is able to deduce the amount of motion the robot has undergone.

All of the multiple view intensity methods use the advantages afforded by rapid acquisition of data but must deal with the considerable difficulties of projection models. That is to say, intensity images can be gathered quickly at rates on the order of 30 frames per second or more. However, information contained in such projections must be supplemented by the establishing of correspondence of points in multiple views before three-dimensional structure or motion may be computed. On the other hand, several studies have made use of range sensing devices that can determine three-dimensional coordinates of a single point. The devices that perform such sensing are significantly slower in the data gathering process than those used for intensity imaging. The acquisition of a typical range image requires from several minutes to several hours.

In this investigation, we adopt the philosophy that the two domains should be used in a complementary fashion. Since intensity images can be obtained quickly but lack directly obtainable 3-D information, they should be used to guide sensing of a limited number of range image points, thus minimizing the data acquisition time in the range domain. As it will be seen the approach taken also avoids many of the problems associated with solving large systems of nonlinear equations and gives a good approximation to motion parameters.

The underlying philosophy of motion parameter extraction is that

information from the intensity image of each view of an object should be used to guide range image sensing for the purpose of directly distilling 3-D coordinates that can be used to derive motion transformations. To this end, a set of feature points is identified in the intensity image. The nature of the feature points is not particularly important, but their extractability should be relatively insensitive to object orientation, assuming that they are not occluded. A second consideration is that it is desirable to link at least some of the feature points into a graph structure that partially represents the object that is being observed. Although this graph structuring is in some cases not absolutely necessary, it can greatly constrain the search when comparing the feature points of an object with those of various models for recognition and correspondence purposes. Such graph structures will generally represent geometric or spatial relationships between feature points.

After determining the basic (partial) graph structure for an object's feature points based solely on intensity information, the range image is sensed to determine the range values at these points. The 3-D coordinate corresponding to each feature point is associated to each node in the graph. A comparison of the information in the object's graph is made with all model graphs and the object is identified. The comparison itself is based upon arc lengths (distances between connected feature points) and angular differences between the arcs. Checking for consistency among the connections between nodes in the model and the candidate node matches in the object further filters out impossible labelings.

After an object is identified then the transformation required to move its model to the current object orientation is computed. This transformation is a 4

x 4 matrix that is the product of rotation and translation matrices. It is derived by treating the feature points for which good graph matching results were obtained as correspondence points and applying a least squares curve fit to compute the elements of the transformation matrix. The transformation matrix itself may be readily decomposed into a three-dimensional translation vector and a single rotation angle if it can be assumed that the moving object has traveled in a plane orthogonal to one of the principal axes. The imposition of such a constraint would be applicable in the case of a vehicle moving on a flat road which was perpendicular to the Z-axis.

If there are several views of the same object, the above process may be applied to each view and the relative (object centered) motion parameters extracted. This is achieved by deriving a sequence of model-to-object transformation matrices as previously described and relating adjacent elements in the sequence to derive object-to-object transformations.

The above methodology for the determination of motion parameters is being implemented in conjunction with the (Technical Arts) laser ranging device recently acquired by our laboratory. A report outlining preliminary results is under preparation.

# PRESENTATIONS, PROCEEDINGS AND PUBLICATIONS

## A. Presentations

1. J. K. Aggarwal, "Dynamic Scene Analysis," at Carnegie-Mellon University, January 1983.

2. J. K. Aggarwal, "3-D Computer Vision - An Introduction," at the ACM Siggraph/Sigart Workshop on Motion - Representation and Perception, Toronto, Canada, April 1983.

3. W.N. Martin, B. Gil and J. K. Aggarwal, "Volumetric Representation for Object Model Acquisition," at the NASA Symposium on Computer Aided Geometry Modeling, Hampton, VA, April 1983.

4. J. Courtney and J. K. Aggarwal, "Robot Guidance Using Computer Vision," at Trends and Application 1983 Conference, Gaithersburg, MD, May 1983.

5. S. Yalamanchili and J. K. Aggarwal, "A Model for Parallel Image Processing," at the International Society for Optical Engineering Annual Symposium, San Diego, CA, August 1983.

6. M. Magee and J. K. Aggarwal, "Intensity Guided Range Sensing Recognition of Three-Dimensional Objects," at the 3-D Workshop of the American Association for Artificial Intelligence, Washington, DC, August 1983.

7. Y.C. Kim and J. K. Aggarwal, "Rectangular Coding of Binary Images," at IEEE Computer Society Conference on Computer Vision and Pattern Recognition, Washington, DC, June 1983.

8. M. Magee and J. K. Aggarwal, "Intensity Guided Range Sensing Recognition of Three-Dimensional Objects," at the IEEE Computer Society Conference on Computer Vision and Pattern Recognition, Washington, DC, June 1983.

9. C.H. Chien and J. K. Aggarwal, "A Normalized Quadtree Representation," at the IEEE Computer Society Conference on Computer Vision and Pattern Recognition, Washington, DC, June 1983.

10. J. K. Aggarwal, "Pattern Recognition Vs. Artificial Intelligence," at the 12th Applied Imagery Pattern Recognition Workshop at University of Maryland, College Park, MD, September 27, 1983.

11. M. Magee and J. K. Aggarwal, "Robot Vision for Location Determination and Obstacle Avoidance" at COMPCON Fall '83, Arlington, Virginia, September 25-29, 1983.

12. J.K. Aggarwal, "Pattern Recognition and Artificial Intelligence," at the IEEE Workshop on Applications of Artificial Intelligence and Signal Processing to Underwater Acoustics and Geophysics Problems, Montreal, Canada, August 1984. (Lead Invited Speaker.)

13. S. Yalamanchili and J.K. Aggarwal, "Parallel Image Processing With the Shuffle Exchange Network," at the IEEE Computer Society Workshop on Computer Vision: Representation and Control, Annapolis, Maryland, May 1984.

14. B. Boyter and J.K. Aggarwal, "Recognition With Range and Intensity Data," at the IEEE Computer Society Workshop on Computer Vision: Representation and Control, Annapolis, Maryland, May 1984.

15. S. Yalamanchili and J.K. Aggarwal, "Algebraic Properties of Some Parallel Processor Interconnection Network," IEEE Computer Society International Conference on Data Engineering, Los Angeles, California, April 1984.

16. M. Magee and J.K. Aggarwal, "Determining the Position of a Robot Using a Single Calibration Object," at the IEEE Computer Society International Conference on Robotics, Atlanta, Georgia, March 1984.

17. M. Magee and J.K. Aggarwal, "Determining Motion Parameters Using Intensity Guided Range Sensing" at the International Association for Pattern Recognition Seventh International Conference on Pattern Recognition, Montreal, Canada, August 1984.

18. C.H. Chien and J.K. Aggarwal, "A Volume/Surface Octree Representation," at the International Association for Pattern Recognition Seventh International Conference on Pattern Recognition, Montreal, Canada, August 1984.

19. B. Vemuri and J.K. Aggarwal, "3-Dimensional Reconstruction of Objects from Range Data," at the International Association for Pattern Recognition Seventh International Conference on Pattern Recognition, Montreal, Canada, August 1984.

20. J.K. Aggarwal, "Algorithm Driven Architectures for Image Processing," at the Workshop on Algorithm-Guided Parallel Architecture for Automatic Target Recognition, sponsored by Naval Research Laboratory, Leesburg, VA, July 1984. (Lead Invited Speaker.)

21. C.H. Chien and J.K. Aggarwal, "Generating Volume/Surface Octrees from Three Orthogonal Views," at the Annual Meeting of Optical Society of America, San Diego, CA, October 29-November 2.

B. Papers


1. W. N. Martin and J. K. Aggarwal, "Volumetric Descriptions of Objects from Multiple Views," IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. PAMI-5, No. 2, pp. 150-158, March 1983.

2. Amar Mitiche and J. K. Aggarwal, "Detection of Edges Using Range Information," IEEE Transactions on Pattern Analysis and Machine Intelligence, Vol. PAMI-5, No. 2, pp. 174-178, March 1983.

3. J. A. Webb and J. K. Aggarwal, "Shape and Correspondence," Computer Vision, Graphics and Image Processing, Vol. 21, No. 1, pp. 145-160, January 1983.

4. B. Gil, A. Mitiche and J. K. Aggarwal, "Experiments in Combining Intensity and Range Edge Maps," Computer Vision, Graphics and Image Processing, Vol. 21, No. 3, pp. 395-411, March 1983.

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